Relay Selection and Resource Allocation for D2D-Relaying under Uplink Cellular Power Control

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***Abstract*—Device-to-Device (D2D) communication underlying 5G cellular networks enable using direct communication between devices as a relay strategy for coverage extension. We consider such a D2D-relaying approach in a scenario where there are multiple candidate devices to be selected as relays. Both backhaul and D2D transmissions are performed in uplink cellular resources, and are subject to cellular uplink power control. We investigate the relay selection and resource allocation problem for D2D-relaying in a multi-user, multi-carrier and multi-cellular network. For this purpose, we formulate a joint optimization problem and propose a simplified relay selection and resource allocation scheme. Using this scheme in a system simulation, we demonstrate that D2D-relaying under uplink power control increases the throughput of cell-edge users significantly.**

I. Introduction

Consistent user experience is one of the most challenging objectives of 5G cellular networks [1]. To achieve this goal, the user experience should be independent from the location of the user in a cell. From this perspective, one of the most important improvements of 5G as compared to 4G technologies should be in the throughput of cell-edge users. To achieve such improvements, novel communication and networking technologies are needed. For example, distributed antenna systems and Ultra Dense Networks (UDN) of small cells have been considered. By shortening the communication distance between the User Equipment (UE) and the infrastructure element, and using wired/wireless backhaul, these techniques have the potential to boost cell-edge throughput [2] [3]. However, as infrastructure networks become denser, the deployment and maintenance costs become larger as well. Accordingly, using Device-to-Device (D2D) relaying to improve system capacity and coverage comes into consideration for future 5G wireless networks [4]–[7]. The underlying idea is that there is a large number of devices that may act as relays, either infrastructure UDN access points without wired backhaul, or other devices such as user-deployed devices, nomadic nodes, or mobile stations, which may act as relay stations to help to convey user traffic to or from the network. In two-hop uplink communication, the access hop is based on D2D communication, whereas the relay hop is a self-backhaul connection based on traditional cellular technologies.

Cooperative communications with relay selection has been widely studied in literature [8]–[10], where a fixed transmission power for both source and relay node is traditionally assumed. The D2D-relaying problem in this paper differs from a conventional relay selection problem due to the Transmission Power Control (TPC) applied by the cellular network [11]–[14]. In a multi-cellular network, uplink TPC is used for two reasons. On one hand, uplink TPC manages the interference between cells, by applying a strict control on the power radiated into neighboring cells. On the other hand, uplink TPC is needed to mitigate the near-far effect. In 4G cellular networks, orthogonality of frequency domain Resource Blocks (RB) is only approximate, and the received powers at the Base Station (BS) on neighboring RBs have to be kept similar to keep intra-cell in-band emission interference low. In [11], [14], a model for uplink D2D relaying is discussed, where cellular power control is used in the backhaul links, whereas the D2D links apply a fixed transmit power. In [11], all D2D links reuse the same resources, whereas in [14], orthogonal resources are used for each D2D transmission. However, the allocation of resources to D2D access links and the D2D transmission power is fixed in the whole network, to keep multi-cell interference under control. In [13], all transmissions are power controlled by the serving BS, and multiple relays are selected to create a virtual MIMO system for the backhaul link. The total transmit power radiated to a cell is not under control, because each of the virtual-MIMO transmitters is separately power controlled, and the interference caused to neighboring cells depends on the selected number of relaying devices. Furthermore, inter-cell interference is modeled by an 'aggressor network', which is independent from the system.

In this paper, we concentrate on D2D relaying in a scenario where a large number of candidate relays is available. Strict cellular power control is applied for all transmissions, including backhaul and D2D. Uplink TPC is based on full compensation of the pathloss between the devices and the serving BS, and received power is restricted per used RB. There is a maximum transmission power, which prevents cell-edge users to achieve high data rates using the direct link to the BS, because power budget limits the number of RBs that can be used. For each UE, either the best two-hop relay path or the direct transmission is selected. Moreover, relays operate in orthogonal resources. This makes both inter- and intra-cell interference predictable, and enables a flexible resource allocation within a cell. We schedule resources to each flow of the users, and the resources scheduled to a relaying flow can be flexibly allocated between the two hops, independently in each flow.

We first show that with a fixed resource allocation to a flow, where the source has sufficient transmit power to reach the destination BS, relaying does not provide any gain under strict cellular power control. The gains in this scenario with strict power control and orthogonal resources comes from flexible resource scheduling. The backhaul hop in a two-hop flow can use a wider bandwidth than the corresponding direct link transmission and, accordingly, a higher end-to-end

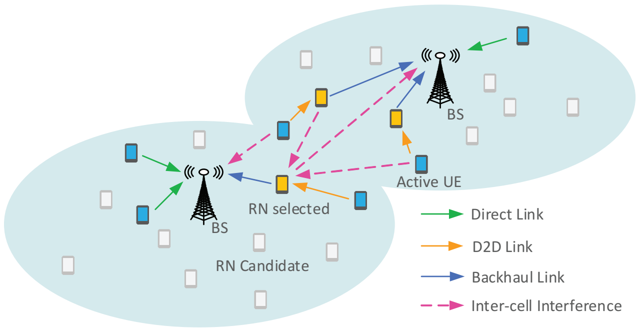

Fig. 1. Illustration of system model, where there are multiple relay candidates, active UEs inside a cell. An UE can choose to use direct link (single hop) or D2D relaying (two hop) for uplink communication. Inter-cell interference is introduced because frequency reuse factor is 1.

rate can be reached. We show that by proper allocation of bandwidth resources among D2D links and backhaul links for D2D relaying, we can capitalize on D2D relaying to increase fairness among users and provide more consistent coverage of uplink data rates to cell-edge users.

II. SYSTEM MODEL AND ASSUMPTIONS

We consider the uplink transmission in a multi-cell cellular network consisting of N_{bs} BSs, indexed by $i = 1, 2, ..., N_{\text{bs}}$. Uplink transmissions are based on SC-FDMA, and the minimum unit of spectrum resources is one RB with fixed bandwidth B_{rb} and time duration. The total number of RBs in frequency domain is M for each cell. On average there are K active UEs and N Relay Node (RN) candidates per cell, locations of UEs and RNs are modeled by a Poisson Point Process. A RN may be either an idle UE or some other relay device. Each UE or RN is associated to the BS that has the smallest pathloss. We use $\mathcal{U}_i$ and $\mathcal{R}_i$ to denote the set of UEs and RNs associated to BS i. To simplify the analysis, we only consider RN candidates that are associated to the same BS as the cell-edge UE. The direct pathloss between UE k and its serving BS is L_k^{dir}, the backhaul pathloss between RN n and the serving BS is L_n^{bh}, and the D2D pathloss between UE k and RN n is $L_{k,n}^{\text{d2d}}$. Inside a cell, we assume that bandwidth resources are orthogonally used by the transmitting devices, so that there is no intra-cell interference. However, because SC-FDMA is sensitive to the in-band emission interference, the received powers of different devices must be kept under control to keep the intra-cell in-band emission interference tolerable. Inter-cell interference is introduced because of frequency reuse factor is one. The cells are assumed to be fully loaded such that all users need an as high throughput as possible. All UEs and RNs are under transmission power control by the serving BS. The system model is depicted in Fig. 1. There are three kinds of links. The direct link is used when an active UE has a good direct channel to BS. The D2D link is the first hop when an active UE uses RN for relaying, and the backhaul link is the second hop between the RN and BS. The relays are half-duplex, which is taken into account when scheduling resources to the backhaul and D2D links. Distance-dependent path loss and shadow fading are considered for all communication links. The pathloss is measured and estimated by the UE or RN and reported to the serving BS.

A. Uplink Transmission Power Control

The transmission power of an UE or RN is controlled by the serving BS to ensure that the received power per RB at serving BS is on the right level. This transmission power is determined by several parameters given to the UE or RN via control channels [15]. The overall transmission power in the data channel is defined as

$$P_{\text{tx}}(L, N_{\text{rb}}) = \min\left\{P_{\max}, N_{\text{rb}}\ P_o\ L^{\beta}\right\}, \tag{1}$$

where $P_{\max}$ is the maximum transmit power, which is assumed to be the same for UE and RN, N_{rb} is the number of RBs allocated for UE or RN, P_o is the target received power per RB at serving BS, β is the cell-specific fractional compensation factor, and L is the pathloss from device to BS. We assume $L = L_0\ d^{\alpha}\ f_s$, where L_0 is average pathloss on cell border including antenna gains, feedline and miscellaneous losses, d is the normalized distance with respect to cell radius R, α is the pathloss exponent, f_s is the log-normal distributed shadow fading. In this paper we use a $\beta = 1$, which corresponds to full pathloss compensation. We assume that pathloss estimation is accurate and the downlink and uplink average pathloss are the same. The actual received power per RB at the BS is

$$P_{\text{rx,rb}}(L, N_{\text{rb}}) = \frac{P_{\text{tx}}(L, N_{\text{rb}})}{N_{\text{rb}}\ L} = \min\left\{\frac{P_{\max}}{N_{\text{rb}}\ L}, P_o\right\}, \tag{2}$$

and the received power per RB at RN for D2D link is

$$P_{\text{rx,rb}}^{\text{d2d}}\left(L^{\text{dir}}, N_{\text{rb}}\right) = \frac{P_{\text{tx}}\left(L^{\text{dir}}, N_{\text{rb}}\right)}{N_{\text{rb}}\ L^{\text{d2d}}}. \tag{3}$$

The relaying problem under cellular uplink power control

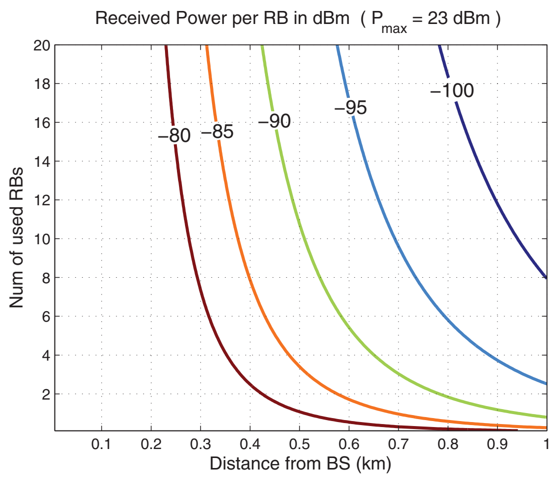

Fig. 2. Uplink power control with different values of P_o when only distance-dependent pathloss is considered and $P_{\max} = 23$ dBm. Each contour curve shows how many RBs a direct or backhaul link can use to guarantee a specified P_o value at BS.

differs from the traditional relaying problems because the transmission power is not fixed and changes according to the differing pathloss to BS and the number of allocated RBs according to (1). If perfect pathloss compensation is performed (with $P_{\max} = \infty$ and $\beta = 1$), relaying is counterproductive. A direct link has sufficient transmit power to meet the power control target irrespectively of the resources allocated. In reality, a UE has a maximum transmission power $P_{\max}$. When the pathloss between UE and BS is too large, and UE has been granted a number of RBs, it is possible that even using the maximum transmission power on these resources cannot fulfill the target received power at BS. Instead of using all the allocated resources for a direct link transmission, the UE can choose to concentrate its power on fewer resources, so that BS should get right received power. To guarantee P_o for the direct link, the maximum number of RBs UE can use is

$$N_{\max} = \left\lceil \frac{P_{\max}}{P_o \; L} \right\rceil, \tag{4}$$

where $\lceil \cdot \rceil$ represents the ceiling function. When only distance-dependent pathloss is considered, we see from Fig. 2 that in a cell of radius $R = 1$ km, to guarantee $P_o = -90$ dBm per RB at BS, an UE at cell-edge can only use one RB for direct link, while an UE or RN at $d = \frac{1}{2} R$ can use up to 10 RBs. Limited by the used number of RBs and $P_{\max}$, the throughput for cell-edge users is very low when using the direct link. If cell-edge user can exploit the availability of a large number of relay candidates in the network to help to forward its traffic, then by allocating more resources among D2D link and backhaul link, the throughput for edge users can be increased.

B. Inter-Cell Interference

The achievable throughputs for the UEs not only depend on the received powers at BSs or RNs, but also on the overall interference powers coming from adjacent cells. In this paper, we are interested in the long-term average throughputs for all UEs, so the average interference levels both at both BSs and RNs are considered. The average SINR at the servering base station i for the direct link of UE k is

$$\gamma_k = \frac{P_{\mathrm{rx,rb}} \left(L_k^{\mathrm{dir}}, N_k^{\mathrm{dir}} \right)}{I_i + P_{\mathrm{N,bs}}}, \tag{5}$$

where N_k^{dir} is the number of RBs used by UE k for direct link, $P_{\mathrm{N,bs}}$ is the thermal noise power per RB at BS. For a backhaul link between RN n and the serving BS,

$$\gamma_n = \frac{P_{\mathrm{rx,rb}} \left(L_n^{\mathrm{bh}}, N_n^{\mathrm{bh}} \right)}{I_i + P_{\mathrm{N,bs}}}, \tag{6}$$

In (5) and (6), the average interference power per RB at BS i is

$$I_i = \sum_{j \neq i} \left(\sum_{k \in \mathcal{U}_j} \frac{w_k \; P_{\mathrm{tx},k}}{L_{k,i}} + \sum_{n \in \mathcal{R}_j} \frac{w_n \; P_{\mathrm{tx},n}}{L_{n,i}} \right). \tag{7}$$

Where w_k, w_n are factors related to inter-cell channel randomization and the activities (both on frequency and time domain) of UE k and RN n. For example, under independent and randomized channel allocation, for a device k which is selected to transmit on N_k RBs all the time, we have $w_k = N_k/M$. I_i depends heavily on the distribution of UEs, the power control parameter β (with fractional power control) and the targeted received power P_o. Under uplink TPC, $P_{rx,\mathrm{rb}}$ at BSs is close to P_o. However, for a D2D link, the received signal power at RN depends on the varying D2D pathloss. For D2D relaying, the targeted received power for D2D should be larger than P_o. Also, the interference powers at RNs have different statistical characteristics compared to BSs simply because uplink TPC is done for the serving BSs, not for D2D links, and some neighbor cell interferers are closer to RNs than BSs. For a D2D link between UE k and RN n, the average SINR is

$$\gamma_{k,n} = \frac{P_{\mathrm{tx}} \left(L_k^{\mathrm{dir}}, N_k^{\mathrm{d2d}} \right)}{N_k^{\mathrm{d2d}} \; L_{k,n}^{\mathrm{d2d}} \cdot (I_n + P_{\mathrm{N,rn}})}, \tag{8}$$

where $P_{\mathrm{N,rn}}$ is the received noise power per RB at the RN. I_n is the interference power per RB at the RN. The instantaneous throughput for a link (with SINR γ and N_{rb} RBs) is approximated by Shannon equation as

$$R = N_{\mathrm{rb}} \; B_{\mathrm{rb}} \; \log_2 (1 + \gamma). \tag{9}$$

III. Analysis of D2D Relaying under TPC

Let us assume that each UE can get at most N_{R} RBs for its flow on average over time. For UEs which are closer to the BS, under strict TPC, they can use more RBs for direct link. For cell edge users, they can only make sure that targeted received power is achieved on fewer RBs at BSs, see Fig. 2 when $P_o = -90$ dBm for example. If there are RNs that are close to a cell-edge UE and at the same time have good channels to BS, then using relaying would help to boost end-to-end throughput performance for cell-edge UE by using more RBs on backhaul hop. For relaying transmission, due to the half-duplex constraint, RN cannot receive and transmit at the same time, we allocate xN^{bh} RBs for backhaul link and $(1-x)N^{\mathrm{d2d}}$ RBs for the D2D link, where x is the fraction of time duration allocated to backhaul link. It should be noticed that the transmission power of D2D link is determined by the direct link pathloss, other than D2D pathloss. As a result, a cell-edge UE would use P_{max} likely. For backhaul link, under TPC, the received power per RB at BS would be P_o. The estimated end-to-end throughput for D2D relaying is:

$$R_{k,n}^{e2e} = \min \left\{ x R_n^{bh}, (1-x) R_k^{d2d} \right\} \tag{10}$$

where $R_n^{bh} = N_n^{bh} \; B_{\mathrm{rb}} \; \log_2(1 + \gamma_n)$ is the instantaneous rate for backhaul link, $R_k^{d2d} = N_k^{d2d} \; B_{\mathrm{rb}} \; \log_2 (1 + \gamma_{k,n})$ is the instantaneous rate for D2D link. R_n^{bh} increases as N_n^{bh} increases, and R_k^{d2d} also increases as N_k^{d2d} increases. For direct link, the end-to-end throughput is:

$$R_k^{dir} = N_k^{dir} \; B_{\mathrm{rb}} \; \log_2(1 + \gamma_k) \tag{11}$$

When using D2D relaying, the resource allocation problem can be formulated as:

$$\max_{x, N_n^{bh}, N_k^{d2d}} \quad x R_n^{bh} \tag{12a}$$

$$\text{s.t.} \quad (1-x) R_k^{d2d} = x R_n^{bh} \tag{12b}$$

$$(1-x) N_k^{d2d} + x N_n^{bh} \leq N_R \tag{12c}$$

$$1 \leq N_n^{bh} \leq \left\lceil \frac{P_{max}}{P_o \; L_n^{\mathrm{bh}}} \right\rceil \tag{12d}$$

$$1 \leq N_k^{d2d} \leq \left\lceil \frac{P_{max}}{P_o \; L_{k,n}^{\mathrm{d2d}}} \right\rceil \tag{12e}$$

$$0 < x < 1. \tag{12f}$$

To maximize (12a), both N_n^{bh}, N_k^{d2d} should be as large as possible. However, the bandwidth resource allocation should also meet with the constraints (12b)–(12f). If (12c) starts to take effect, then larger bandwidth should be allocated to the better hop. In this paper, an efficient resource allocation

Algorithm 1 BH/D2D Resource Allocation

INPUT: $L_{k,n}^{\mathrm{d2d}}, L_n^{\mathrm{bh}}, L_k^{\mathrm{dir}}$, and average number N_R of RBs
OUTPUT: $R_{k,n}^{e2e}$, N_k^{d2d}, N_n^{bh}

1: $N_n^{bh} \leftarrow \left\lceil \frac{P_{max}}{P_o\ L_n^{\mathrm{bh}}} \right\rceil$.
2: $N_k^{d2d} \leftarrow \left\lceil \frac{P_{max}}{P_o\ L_{k,n}^{\mathrm{d2d}}} \right\rceil$.
3: Calculate R_k^{d2d} and R_n^{bh} .
4: Calculate time partition $x \leftarrow \frac{R_k^{d2d}}{R_k^{d2d}+R_n^{bh}}$.
5: **if** $(1-x)N_k^{d2d} + xN_n^{bh} \leq N_R$ **then**
6:     break;
7: **else if** $R_k^{d2d}/N_k^{d2d} < R_n^{bh}/N_n^{bh}$ **then**
8:     $N_k^{d2d} \leftarrow \left\lceil \frac{N_R - xN_n^{bh}}{(1-x)} \right\rceil$, **go to 3.**
9: **else if** $R_k^{d2d}/N_k^{d2d} \geq R_n^{bh}/N_n^{bh}$ **then**
10:     $N_n^{bh} \leftarrow \left\lceil \frac{N_R-(1-x)N_k^{d2d}}{x} \right\rceil$, **go to 3.**
11: **end if**
12: $R_{k,n}^{e2e} = xR_n^{bh}$, return.

algorithm is proposed to solve the above optimization problem, see algorithm 1 for full details.

To show the gain of D2D Relaying under power control, analysis for 1-Dimensional setting with distance-dependent pathloss is performed. As depicted in Fig. 3, distance between

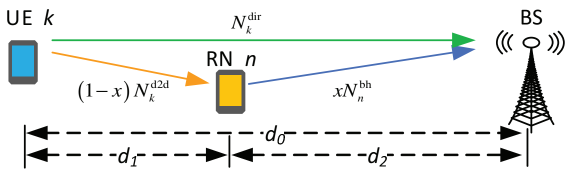

Fig. 3. D2D Relaying – 1-Dimensional example

UE k and serving BS is d_0, between UE and RN n is d_1, between RN and serving BS is $d_2 = d_0 - d_1$. Assume the number of RBs used for direct link is N_k^{dir}. For a RN at different positions, algorithm 1 is adopted to find the optimal resource allocation. We can see from result in Fig. 4 that the optimal RN position is $d_2 = 0.5\ R$. At this optimal position, the instantaneous throughputs for the direct link, D2D link and backhaul link are plotted in Fig. 5.

IV. Relay Selection and Resource Allocation Scheme

In a cell with multiple users, one has to allocate resources among users. We assume that for each cell, the pathlosses L_k^{dir}, L_n^{bh} and $L_{k,n}^{\mathrm{d2d}}$ ($k \in \mathcal{U}_i$, $n \in \mathcal{R}_i$) are given. We search for a proportionally fair solution to the joint relay selection and resource allocation problem. Let us use X_k to indicate whether active UE k uses relaying or direct transmission, $X_k = 0$ means that UE k communicates directly with BS, $X_k = n$ means that UE k uses RN n to relay its data. For this, we need to search for X_k, N_k^{d2d}, $N_{X_k}^{\mathrm{bh}}$ and N_k^{dir}, so that the proportionally fair utility function

$$U = \sum_{k \in \mathcal{U}_i} \log\left(R_k^{e2e}\right) \tag{13}$$

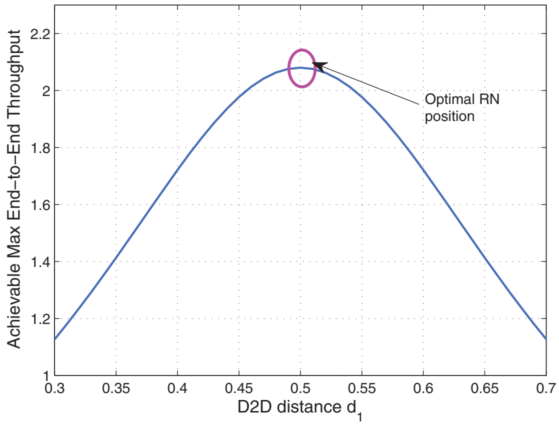

Fig. 4. Best RN position for cell-edge UE with $d_0 = R$

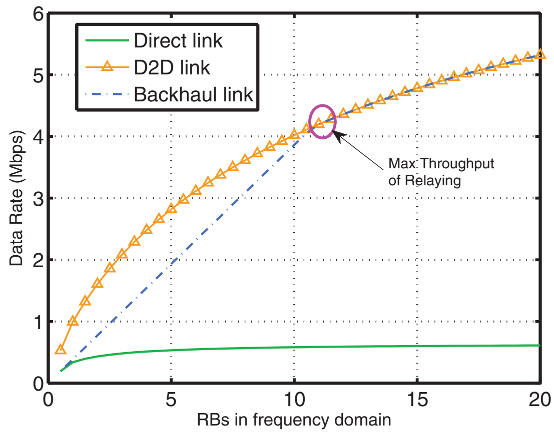

Fig. 5. Example: D2D relaying gain for cell-edge UE

is maximized in each cell. The constraint for this optimization problem is

$$\sum_{k \in \mathcal{U}_i} \left(N_k^{\mathrm{dir}} + (1-x_k)N_k^{\mathrm{d2d}} + x_k N_{X_k}^{\mathrm{bh}}\right) = M. \tag{14}$$

In general, the joint relay selection and resource allocation problem under uplink power control is hard to be solved due to its mixed integer character and the nonlinearity brought by TPC.

A. *Joint Relay Selection* (RS) and Resource Allocation (RA) Algorithm

With D2D relaying, we divide the resource allocation scheme into two step. Firstly, to guarantee the fairness among all the active users in one cell, the RBs are allocated to each user flow evenly. Secondly, the resources available for each user is allocated to D2D link and backhaul link using the algorithm 1. The relay selection here is done together with the resource allocation, see algorithm 2. For comparison, in the scenario where D2D relaying is not adopted (only direct links are used), the resource allocation in one cell is also presented here. Firstly, we sort the UEs in current cell according the pathloss to BS, and calculate $N_{\mathrm{rb}}^{\mathrm{rest}}/N_{\mathrm{UE}}^{\mathrm{rest}}$, where $N_{\mathrm{rb}}^{\mathrm{rest}}$ is number of remaining RBs and $N_{\mathrm{UE}}^{\mathrm{rest}}$ is the number of UEs not served. Secondly, starting from the UE having the largest pathloss, $N_{\mathrm{x}} = \min(N_{\mathrm{rb}}^{\mathrm{rest}} / N_{\mathrm{UE}}^{\mathrm{rest}} , \lceil P_{\max}/(P_o\ L) \rceil)$ RBs are allocated to this UE to make sure that the received power per RB at BS is P_o, then we update new $N_{\mathrm{rb}}^{\mathrm{rest}} = N_{\mathrm{rb}}^{\mathrm{rest}} - N_{\mathrm{x}}$, new $N_{\mathrm{UE}}^{\mathrm{rest}} = N_{\mathrm{UE}}^{\mathrm{rest}} - 1$. Then the remaining RBs are allocated among the not served UEs in the same way until all UEs in this cell are served.

Algorithm 2 Joint RS and RA for D2D Relaying

There are $\hat{K}$ UEs and $\hat{N}$ RNs in current cell, the UEs in this cell are denoted by $k = 1, 2, ..., \hat{K}$, RNs are denoted by $n = 1, 2, ..., \hat{N}$, $N_R = M \big/ \hat{K}$.
for $k = 1$ to $\hat{K}$ **do**
  Calculate $N_{\max}$ using (4), $N_k^{dir} \leftarrow \min(N_{\max}, N_R)$, calculate R_k^{dir} using (11).
  for $n = 1$ to $\hat{N}$ **do**
    if $L_n^{\mathrm{bh}} \geq L_k^{\mathrm{dir}}$ or $L_{k,n}^{\mathrm{d2d}} \geq L_k^{\mathrm{dir}}$ **then**
      $R_{k,n}^{e2e} = 0$, break;
    else
      Calculate $R_{k,n}^{e2e}, N_k^{\mathrm{d2d}}, N_n^{\mathrm{bh}}$ using **Algorithm 1.**
    end if
  end for
  $R_k^{e2e} \leftarrow \max\left(R_k^{dir}, R_{k,1}^{e2e}, ..., R_{k,\hat{N}}^{e2e}\right)$, and assign the best relay X_k for UE k. If $R_k^{e2e} = R_k^{dir}$, direct link is used for UE k.
end for

V. Simulation Results

The simulation parameters is listed in table I. We assume an urban environment with a propagation exponent of β =3.76, and log-normal shadowing. The simulation area is square with wrap-around edges. The TPC parameters $P_o = -90$ dBm and $\beta = 1$ are used to ensure that the multi-cell system is properly working [17]. The I_{i} and I_{n} are first estimated, and then to be refined during simulation in an iterative process. The average interference power experienced at each RN or BS is computed after the relay selection and resource allocation have been done. For each iteration, $N_{\mathrm{bs}} \times K$ UEs and $N_{\mathrm{bs}} \times N$ are dropped inside the simulation scenario, pathlosses are calculated using distances and the generated shadow fadings. The joint RS and RA algorithm is used to find the best relay for each active UE and to determine the number of RBs used by each link. Finally, the actual SINRs at each BS and RN are calculated using the pathlosses, transmission powers and the resource allocation results for the whole system.

TABLE I. Simulation Parameters

Simulation Parameter	Symbol	value
Number of BSs	N_{bs}	10×10
Average active UEs per cell	K	10
Average relay candidates per cell	N	200
Inter-site Distance	D	1.732km
Pathloss exponent	α	3.76
Pathloss including antenna gain at cell border	L_0	114 dB
TPC parameter	β	1
Targeted received power per RB	P_o	-90 dBm
UE maximum Tx power	P_{max}	23 dBm
Standard deviation of SF	δ_{SF}	8 dB
Thermal noise level at BS	$N_{0,\mathrm{bs}}$	-170 dBm/Hz
Thermal noise level at RN	$N_{0,\mathrm{rn}}$	-165 dBm/Hz
Resource block bandwidth	B_{sub}	200 kHz
Number of RBs for each cell	M	200

A. Relay Selection Result

The relay selection result in Fig. 6 shows that the best relay is heavily dependent on the location of RN and the result is very similar to [18]. The dominant component in pathloss comes from the locations of the nodes. In our simulation, we found that the best relays for cell-edge users are mainly located at half-distance locations. This is because that RNs at these places can use more RBs and are simultaneously close enough to cell-edge UEs to get higher D2D SINRs.

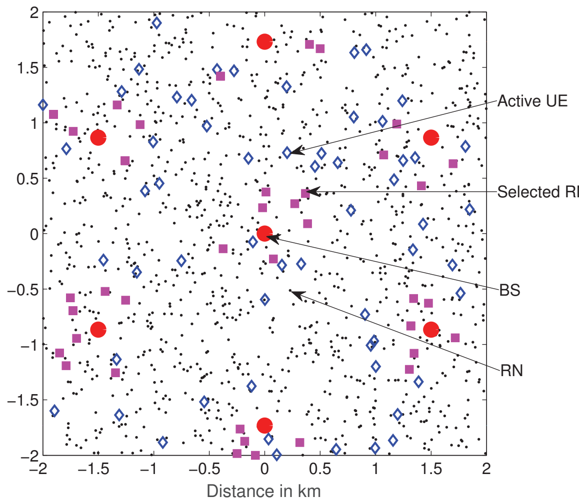

Fig. 6. Relay selection results

B. SINR and throughput performance

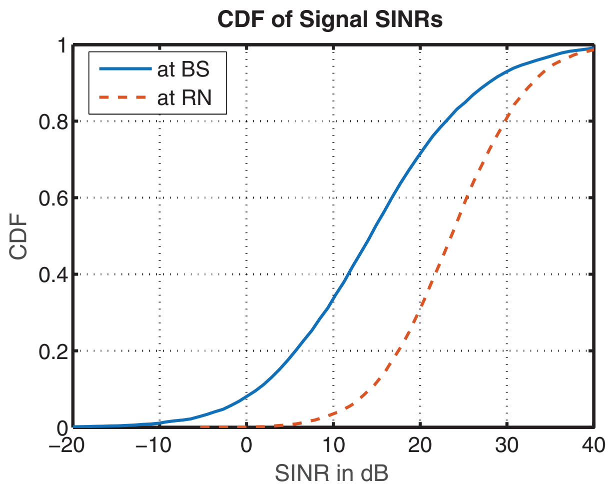

Fig. 7. SINR at base stations and relay nodes

The SINRs in the simulation are explicitly computed using the pathloss values and transmission powers. It can be seen from Fig. 7 that that average SINR experienced at selected RNs is better then at BSs. As TPC is performed for BSs, not for

RNs, the received signal powers per RB at RNs are larger than P_o. Fig. 8 shows the throughput performance of D2D-Relaying

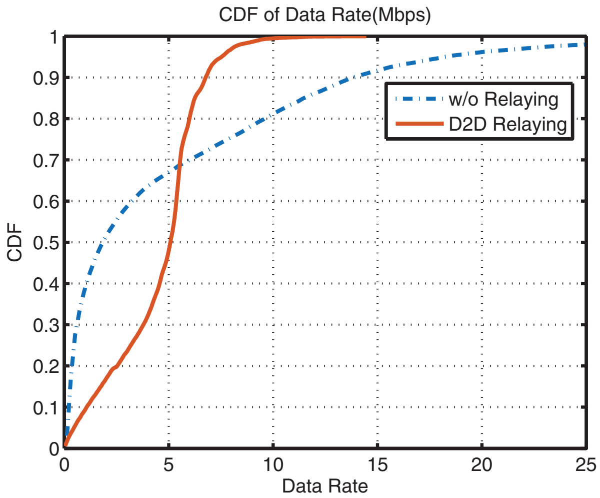

Fig. 8. Throughput performance of D2D-Relaying

and without D2D-Relaying. In the scenario without D2D-Relaying, UEs close to BSs use more resources than cell-edge users. Despite attempting proportional fairness in scheduling, cell-edge UEs simply do not have sufficient power to use their fair share of resources. In the D2D-Relaying scenario, UEs close to BSs share the RBs equally with cell-edge UEs. With D2D-Relaying, cell-edge UEs can leverage the availability of multiple devices to use more RBs for their flows. Using D2D-relaying, cell-edge throughput at 10th percentile shows an improvement of more than 300%, while there is a slight loss in average system throughput. In the scenario without D2D relaying, all RBs are used for transmitting data to the BS, with the target P_0, whereas in the D2D relaying scenario, some RBs are used for D2D transmissions, which do not contribute to E2E throughput directly . The negative average effect of this is counteracted by the decrease in the average interference level due to relaying—the average transmit power in a cell becomes lower, so the co-channel interference from other cells is lower. In the simulated scenario, these two effects almost cancel. Finally, the fairness metric related to (13) shows an 90% improvement by using D2D-Relaying.

TABLE II. SIMULATION RESULTS - PERCENTILE THROUGHPUT

Scenario	Average	10th	50th
w/o D2D Relaying	5.05 Mbps	0.23 Mbps	1.8 Mbps
with D2D Relaying	4.86 Mbps	0.95 Mbps	5.0 Mbps
D2D Relaying Gain	-3.8%	313%	178%

VI. CONCLUSIONS

In this paper, we studied a D2D-relaying enabled cellular network in uplink. We considered a multi-user, multi-carrier and multi-cell network with uplink power control to mitigate the inter-cell interference and in-band emission interference. With power control, the relay selection problem is different from that without, due to the constant receive powers per RB at BSs. To enable D2D-relaying, the relay selection, resource allocation and power control problem must be addressed together. We formulated this mixed problem as an optimization problem. We used system simulation to study the performance of a simplified scheme. The simulation results demonstrate that via proper resource scheduling, D2D-relaying under power control increases throughput performance for cell-edge users significantly, which results in consistent user experience.

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